NEW MULTILATERAL WELL ARCHITECTURE

IN HETEROGENEOUS RESERVOIRS

A Thesis

by

HONGQIAO JIA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2004

Major Subject: Petroleum Engineering

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Approved as to style and content by:

Peter Valkó (Chair of Committee)	Robert A. Wattenbarger (Member)
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ABSTRACT

New Multilateral Well Architecture
in Heterogeneous Reservoirs. (May 2004)

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Multilateral well technology has been widely used in the world oil fields. There still has technical limitation of these kinds of well structure. This thesis presents a new multilateral well architecture which is more flexible and economical. The performance of new multilateral well in heterogeneous reservoirs is studied, and that is compared with vertical well architecture also.

In order to study the productivity of new multilateral wells, we use a numerical simulation method to set up heterogeneous reservoir models. The three reservoir models included anisotropic permeability, shale multi-layer, and flow units. Under a pseudo-steady-state, the productivities of horizontal laterals and deviated laterals are calculated and compared. We find that new multilateral well architecture has good performance in heterogeneous reservoir. The heterogeneous properties of reservoirs influence the productivity of horizontal laterals more than deviated laterals. The shale multi-layer and flow units that dominate the fluid flow in reservoirs are important for reservoir characterization.

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TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

1.1 Statement of Problem

Multilateral wells have potential benefits in reservoir exploitation. Some reservoir applications of multilateral technology have been discussed, [1-7]and the need to identify and quantify the reservoir benefits of multilateral wells has received attention. With applications anticipated from deepwater to the arctic, from heavy oil to gas condensate, and from small isolated lens to giant fields, this technology has been widely used in production engineering. However, it seems that most of the computations and models available are strongly related to the geometry limited by current technology.

As the traditional multilateral well still has some limitation in heterogeneous reservoir application, in this thesis, we study a new multilateral architecture that consists of a main horizontal well and some additional feeder laterals connected to it. In this new technology, the horizontal well is not been perforated and it is penetrating almost the total reservoir length. On the other hand, the feeder laterals are completed separately. The first task in evaluating the economic benefits of the suggested new multilateral well architecture would be to identify the types of reservoir applications for which they may be used. The impact of heterogeneity of the reservoir on well productivity has been studied in several recent publications. [8-13]

The problem studied in this thesis is how the heterogeneity affects the overall productivity of the new multilateral well in a reservoir. First, based on ideal homogenous reservoir, we study the permeability anisotropy in the reservoir, which means different permeability in horizontal and vertical directions. Second, we study

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This thesis follows the style of the *Journal of Petroleum Technology*.

the shale layer reservoir that the horizontal multi-layers have their own permeability. After that, more complex heterogeneous reservoirs are studied, which have some regions that can be defined as flow units.

In order to investigate these heterogeneous reservoirs, we build several simulation models. The overall productivity is investigated under various reservoir conditions. In this work, we apply up to date characterization techniques to assess the productivity of the new architecture.

1.2 Literature Review

In this thesis, we present a new multilateral well architecture. In order to study into performance of it, we investigate some technical articles. The scope of these literatures covers the multilateral well technology and characterization of heterogeneous reservoirs.

On one hand, the technology of multilateral well has been investigated. [1-7] A. Retnanto *et al.*[1] studied the optimal configurations of the multilateral well. Their paper investigated several configurations of multilateral well, and discussed the advantages and drawbacks of them. They studied the performance of six different configurations, and found that the length and number of branches could be optimized. These six configurations included multi-branched wells (Fig. 1.1a), fork wells (Fig. 1.1b), several laterals branching into one horizontal mother hole (Fig. 1.1c), several laterals branching into one vertical mother hole (Fig. 1.1d), dual opposing laterals (Fig. 1.1e) and stacked laterals (Fig. 1.1f).

Based on several laterals branching into one horizontal mother hole (Fig. 1.1c), in this thesis, we present new multilateral well architecture that will been discussed later. For the new well architecture, the laterals are separately completed with horizontal mother hole. The completion methods we base on TAML (Technical Advancement of Multilateral) classification matrix that mentioned in P. Vullinghs's article. [2] In their studies, the complementary technologies of different level junctions for multilateral well have been described. Their paper presented level 1, level 2 junctions in the Southern Gas Basin in the Southern North Sea, level 4 junctions in the Central and Northern Sectors, and level 6 junction in Bakersfield. For new multilateral well architecture, from level 1 to level 4 junction can be selected and applied. The junctions level higher than level 4 are complicated and rarely used.

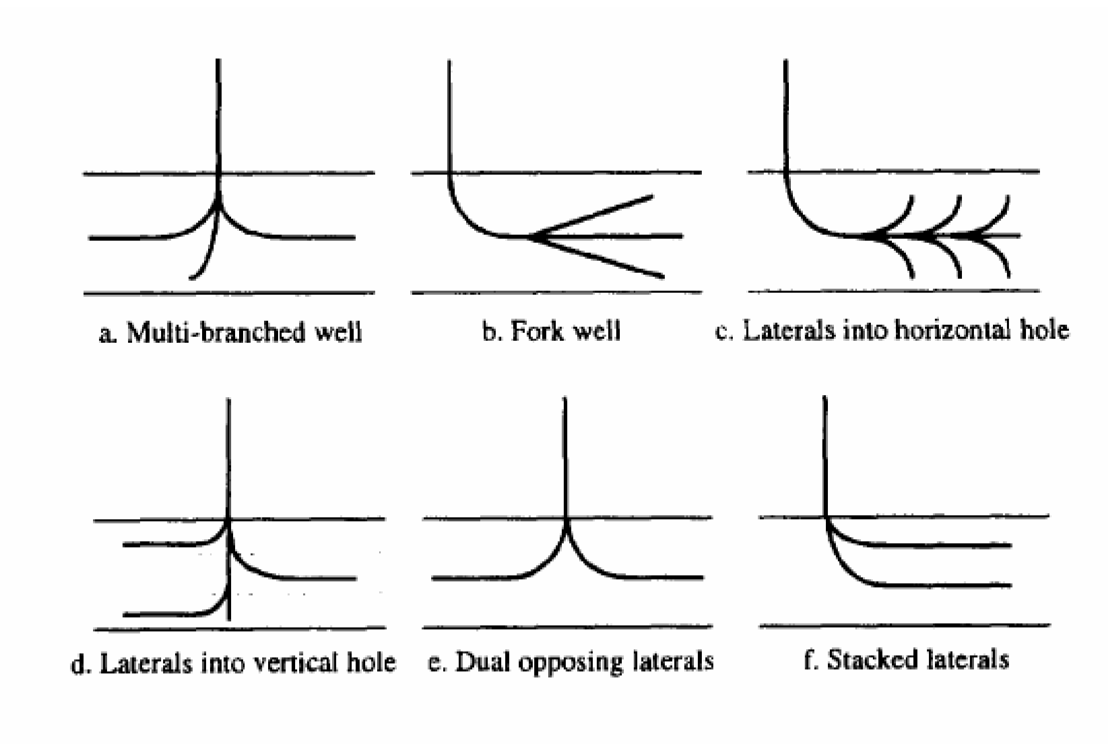


Fig. 1.1 Multilateral well systems

The performance of multilateral well has been studied in some articles.[4-7] A. Retnanto and M.J. Ecnomides [4] presented the performance of multiple horizontal well laterals in low to medium permeability reservoirs. They summarized the general productivity index model. The productivity index J, is given by

$$J = \frac{q}{\overline{P} - P_{wf}}$$

where q is the daily production, $\overline{P}$ is the reservoir average pressure and P_{wf} is the well flowing pressure.

They studied different well configurations under the permeability anisotropy condition. They stated that multiple laterals in low-to-moderate-permeability reservoir can maintain high production. In our thesis, we use productivity index to compare and investigate the performance of the new well architecture.

Abdel-Alim H. EI-sayed *et al.* [5] presented detailed equations to be used for calculating production rate of multilateral wells, both planner and stacked. They discussed the factors affecting the production rate in comparison to a horizontal well. They found that formation thickness, number of laterals and anisotropy of reservoir affect production rate of multi laterals. Multilateral wells are very effective in anisotropy reservoirs, specially stacked laterals (Fig. 1.1f). Based on their research, we not only studied the performance of new multilateral well with different lateral density but also studied the horizontal laterals and deviated laterals in the heterogeneous reservoirs.

For prediction performance of the multilateral well, J.R. Salas *et al.* [6] used analytic and numeric modeling techniques. Their results showed how multilateral well productivity depends on wellbore geometry. Reservoirs with greater heterogeneity were shown to have greater potential benefits from adding multilateral side-branches to an existing wellbore.[6] They also mentioned the gas coning and water flood in reservoirs, which is useful for our future study of new multilateral well technology.

On the other hand, in order to investigate the performance of new multilateral well architecture in heterogeneous reservoirs, we studied the characterization of heterogeneous reservoirs with permeability anisotropy, shale layers and flow units. [8-13]

Firstly, the permeability anisotropy of heterogeneous reservoirs have been investigated. Dongseong Lee *et al.* [8] presented stochastic modeling for anisotropy of heterogeneous reservoirs. In their study, a new method was proposed to characterize the heterogeneous anisotropic reservoir by integrating well testing data and geological data. C. Wolfsteiner [7] presented a model for productivity of non-conventional wells in heterogeneous reservoir. In their work, it shown permeability anisotropy influenced the performance of the productivity of the multilateral well. Based on their research, we use the ratio of vertical and horizontal permeability of the reservoir to describe the permeability anisotropy in new multilateral well simulation models.

Secondly, the shale layers in the reservoir have been studied. Lu Xiaoguang *et al.* [9] presented stochastic modeling technique for heterogeneous multi-layer reservoir. Their methods included sequential indicator simulation (SIS), truncated Gaussion simulation (TGS), and sequential Gaussian simulation (SGS) and random walk simulation (RWS). In their works, 3D depositional microfacies distribution models were established by using a single layer as a unit. The reservoir characterized by multi-layers in vertical, small thickness of a single layer, big differences in reservoir physical properties, and serious heterogeneity both vertically and horizontally.

Thirdly, the characterization of flow units has been investigated. K. Aminian *et al.*[11] used statistical and artificial intelligence techniques to identify flow units based on limited data. Initially, stratigraphic and petrograpgic analysis of cores, correlation of logs, and major rock types were combined to describe various sedimentary bodies or “facies”(Montoe,1992) that have distinct physical, chemical and biological attributes within the formation. [11] Within a given facies the reservoir properties can vary significantly. This variation has led to a further subdivision known as Flow Units.

David K. *et al.* [12] used the pore geometric attributes to predict permeability and define hydraulic flow units in a mature, heterogeneous, shallow shelf carbonate reservoir (SSC reservoirs). In the flow units, the basic relationship between porosity and permeability exhibits a considerable degree of scatter. But, porosity and permeability are closely related for each rock type. The rock type relationship with permeability has an error range of less than one-half decade for most samples. On the log graph, the permeability and the porosity have a correlation of linear regression.[12] The regression lines of permeability vs. porosity have different slopes for different rock types. The steps to set up permeability in heterogeneous reservoir model are as follows.[12]

1. Assume x direction as a maximum principal direction and determine the statistics of the maximum principal direction as desire.

2. For x direction permeabilities, generate random variables with the normal distribution and the desired statistics by using sequential Gaussian simulation method.

3. To get the log-normal permeability field, the step of exponentiating the normal field is taken.

4. Repeat the above procedures for generating a permeability field of the minimum principal direction, y.

5. Assign the values above for x as x direction grid block permeabilities and permeabilities for y as y direction grid block permeabilities. Many different multi lognormal permeability models are generated.

Based on David K. ’s works, we set up simulation models with flow units in which there are different relationship between permeability and porosity.

1.3 Methodology and Procedure

As the new architecture has distinct potential benefits, we study its performance in the heterogeneous reservoir. In our research, we build the new well architecture model in which the main horizontal section is not perforated, and it contains, however, several pre-prepared junctions. Several feed wells then connected the main horizontal section. As the feed well and main well are separated, the new architecture has more flexibility in complicated reservoir conditions.

First, multilateral well performance was investigated in a homogeneous reservoir model. In this base model, we build a rectangular reservoir with a new architecture multilateral well. The well has a main horizontal line and some feed laterals that are flexible to open or shut in. Branch density and penetration of laterals are the two basic parameters that most affect the overall productivity. Assume that a multilateral well architecture must be designed to drain the net pay for a given reservoir. The very first question that arises is: How many of feeder laterals should be drilled? The next issue is: how far should these laterals penetrate (from the junction point) to the bulk of the reservoir? While this decision depends upon the cost of drilling and completion of unit length of a feeder lateral, various additional factors such as hydrocarbon in place, reservoir structure, driving mechanism, permeability anisotropy and heterogeneity will affect the final answer. Our strategy here is to start from the simplest assumptions and understand the main factors, leaving the additional details for later studies of particular individual reservoirs.[14]

Second, different kinds of formation heterogeneity are then added to the basic homogeneous reservoir simulation model. On one hand, an anisotropic reservoir model is been built, which has variable ratio between vertical permeability and horizontal permeability. This work investigates how the ratio of horizontal and vertical permeability plays an important role in the overall productivity index of the horizontal laterals and deviated laterals. Also, in this case we consider other factors affect the well performance, like the well penetration and lateral density. On the other hand, a heterogeneous reservoir with shale layers is set up in simulator. In heterogeneous reservoir conditions, the shale layer always has lower permeability than the reservoir sand layers. Sometimes it will block the reservoir fluid flow and decrease the well productivity. In this case, we compare the different performance results between the horizontal laterals and deviated laterals, and found the best scheme of well structure.

After permeability of anisotropic reservoir and shale layers have been investigated, our further study focus on the more complicated heterogeneous conditions. The reservoir model should begin at pore level. Integration with depositional and diagenetic data from geological analysis allows for determination of the area compartmentalization and permeability distribution in reservoirs. [12] In these models, the permeability is variable with the porosity of the reservoir. We will investigate the performance of the new multilateral well under the reservoir with separated flow units.

CHAPTER II

NEW MULTILATERAL WELL ARCHITECTURE

2.1 Technology of New Multilateral Well Architecture

In this thesis, a new multilateral well architecture is presented, which consists of a horizontal well penetrating almost the total length of reservoir, and some additional feeder laterals connected to the horizontal well. One end (or possibly the middle) of the horizontal well is the point of the onset of vertical lift (natural or artificial) and hence connected to a vertical section reaching the surface or the mudline. In the "reservoir" or rather "unit" considered, there is only one vertical conduit (vertical section) working as production string. The main horizontal section is NOT perforated. It contains, however, several pre-prepared junctions (possibly several dozens.) The diameter and completion type of the vertical and the main horizontal sections are such that they maximize pipe-flow capacity. There is no need for good connection between the horizontal wellbore and the surrounding reservoir, in fact they should be perfectly isolated. The vertical and the main horizontal section are less like traditional petroleum producing wells, rather they are sophisticated underground pipelines. They are not supposed to be readily accessible with any well intervention tool and certainly not prepared for accepting any drilling tools, once cemented. The junction equipment is placed during the drilling of the main horizontal well and it is cemented together with the main horizontal section. The pressure and structural integrity of these junctions is critical requirement. This integrity does not have to be compromised by any additional requirement present in traditional multi-lateral technology, such as potential capability of future well interventions, requirement for formation damage control during the drilling or ability to accept drilling tools in a later phase. [14]

All additional drilling activity in the reservoir starts from one or more other locations on the surface. One typical example would be two vertical wells drilled on both sides of the reservoir, one left and one right from the location of the main horizontal well. Those vertical wells serve as kick-off wells for several multi-laterals, drilled basically in a direction perpendicular to the main horizontal section. At the end point of feeder lateral it is connected to the main horizontal well using the pre-pepared junction point. The laterals, which are basically perpendicular to the main horizontal section, may be completed in several ways, most likely, however, the completion will concentrate on maximizing inflow potential, without compromising it by additional requirements. For instance, relatively slim holes are acceptable and they can be regarded as partly disposable, because it is usually less capital expenses to drill another feeder lateral then repair (workover) any of them. They will certainly not be prepared to accept drilling tools in a later phase and might be completed open hole, frac-packed, etc. This structure can be better understood from the figure below (Fig. 2.1)[14]

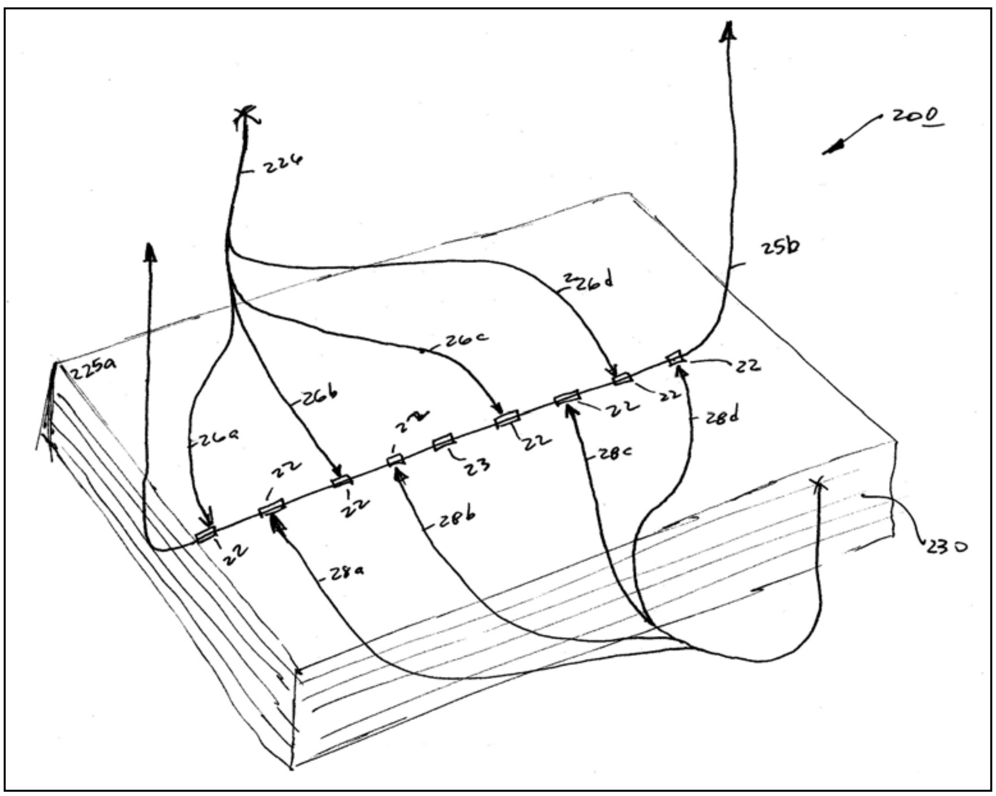


Fig. 2.1 Flexible multilateral architecture[14]

In Fig. 2.1 detail 25b is a parent well with intersection points (detail 22) placed in the casing. Well 226 is then drilled with multiple lateral feeder wells 26 a,b,c,d all connecting into the parent well. The casing of the feeder wells intersects the parent well casing and is mechanically connected and sealed at the intersection points. Production flows through the toe of the feeder well into the parent wellbore to be lifted to the surface. A plug is used in the feeder well to prevent cross flow or pressure transition exposures at the junctions between feeders (26) and the access well (226). Flow controls and sensors may be placed in the feeder wells just outside the intersection points to control contribution from each feeder well and intelligent well controls/communication are only required in the backbone production well (25b). [14]

To reduce the risk of losing production due to a single event compromising a production well, one or more redundant production wellbores (225a) can be interconnected to provide multiple production flow paths. Production tubing, full wellheads, flowlines, etc are not required in the feeder wells but each feeder well can be fractured, independently serviced, etc without closing all production of the well network in contrast to most current multilateral well designs. Since feeder wells are not carrying all production of the well network, they can be smaller in diameter. The production well is a larger wellbore to handle large flow rates. In a deepwater environment, only the production wells need to be connected to the production facility thus reducing riser weight, platform buoyancy requirements, platform space requirements, etc. [14]

2.2 Advantage of New Multilateral Well Architecture

In recent years, multilateral well technology has used widely used in oil field (Fig. 2.2). But It still has some technique limits by architecture. As an example of specific problems that can be solved by the new technology we consider the narrow drilling window between pore pressure and fracturing pressure in an ultra deepwater reservoir (see Fig. 2.3). In traditional multi-lateral drilling, the narrow window allows minimum flexibility during both the drilling of the mother bore and during the kick-off plus drilling plus junction-completion phase for any of the laterals. In the case of the new well architecture, the drilling and completion of the main horizontal section should still satisfy the basic constraints, but the drilling and completion of the laterals is a completely independent process. [14]

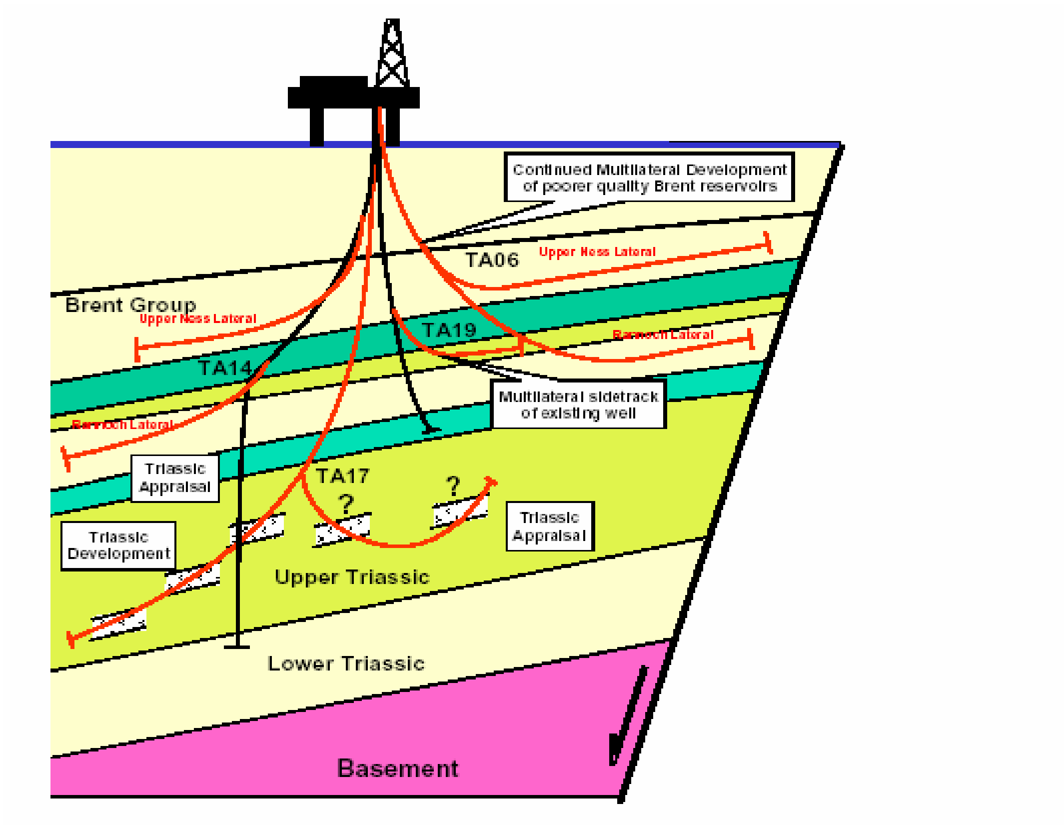


Fig. 2.2 Current state-of-the-art multi-lateral technology application[2]

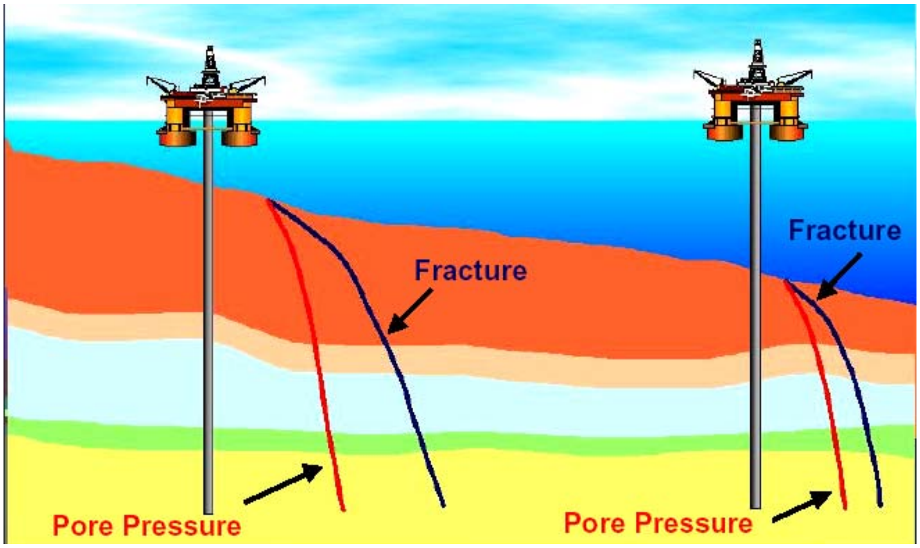


Fig. 2.3 Illustration of a specific problem related to ultra-deepwater reservoirs [14]

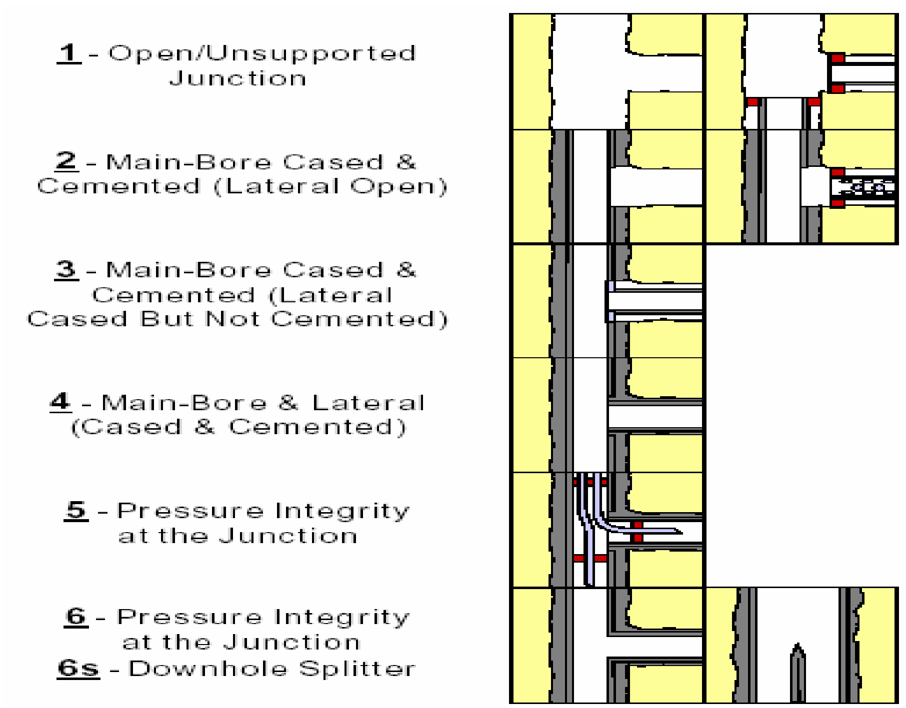


Fig. 2.4 TAML multi-lateral complexity matrix [2]

We note that the new well architecture would provide a minimum Level 4 (or higher) junction integrity according to the TAML specification shown in Fig. 2.4. In current applications Level 4 or higher junctions are rare, because of the inherent conflict of completing a complex junction and providing flexibility for further drilling, kick-off, etc.[14]

From a purely reservoir engineering point of view many of the above advantages are difficult to quantify at this level of the investigation. It is possible, however, to investigate quantitatively the productivity of the new well architecture. It is obvious from Fig. 2.1, that the wellbore structure can be idealized as a main horizontal wellbore feeded by parallel laterals. The idealized architecture is illustrated in Fig. 2.1. The reservoir essentially contains a vertical well bore that conducts the reservoir fluid to the surface. From this vertical, a main horizontal section is drilled, essentially penetrating the entire reservoir in the direction of its larges horizontal dimension. All feeder laterals are connected to the main horizontal section at the pre-prepared junction points. The laterals being perpendicular to the main horizontal section, penetrate in the direction of the smallest horizontal dimension.[14]

The advantages and disadvantages of the suggested new well architecture can be understood in view of the current technology, illustrated in Fig. 2.1.Some of the potential benefits of the novel well design scheme include: [14]

- Reduced overall wellbore drilling cost and time
- Increased ultimate recoveries
- Reduction in wellhead count on seafloor and land; with related reduction of environmental footprint
- Provides improved flow assurance for deepwater and arctic developments by placing “pipelines” and “manifolding equipment” at reservoir depth and temperature
- Reduced well construction risk

- Improved clean up
- Possibility of addition of laterals by drilling outside the production bore and hence causing no interruption in the production process
- Improved production security by providing redundant surface production points; possibility of remedial service from outside the production bore;
- Mechanically sealed junctions with full casing integrity eliminate one of the main failure point in other multi-lateral designs;
- Provision of improved reservoir management & control, including reduced crossflow; isolating watered sections; enabling new smart-well control technology.

CHAPTER III

SIMULATION METHODOLOGY

3.1 Basic Simulation Model

Two kinds of multilateral well models are built in the simulator. Fig. 3.1 shows the “fish bone” horizontal lateral model, and Fig. 3.2 gives the deviated lateral model in which the wellbore direction of legs is not parallel to one of the local coordinate axes. In these two models, we perforate each of the laterals, and the main horizontal wellbore is not perforated.

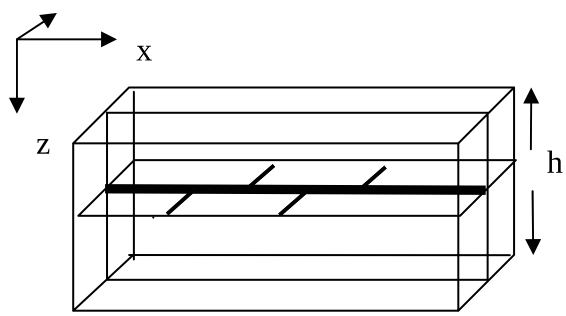


Fig. 3.1 Horizontal lateral mode

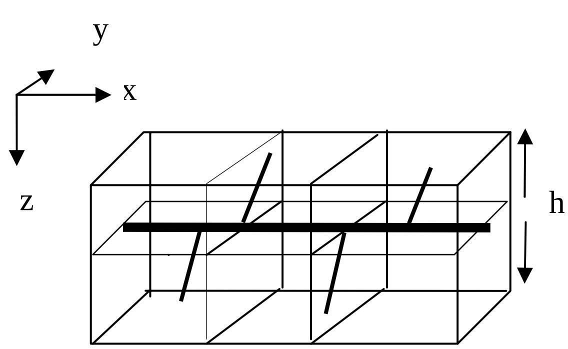


Fig. 3.2 Deviated lateral model

In this research, an undersaturated oil reservoir is considered. The reservoir is assumed to be cubic in shape. The main horizontal well is drilled in the X direction while the laterals are drilled in the Y direction. The important reservoir properties are summarized in Table 3.1. The main horizontal well is at a depth of 5055 ft. For this single phase flow simulation the initial reservoir pressure is assumed to be 4000 psia.

The properties of the basic homogeneous reservoir model listed in Table 3.1. Fig. 3.3 and Fig. 3.4 show the well architectures of the CMG simulation models. In Fig. 3.3, the well has 60 laterals that can easily be opened and closed. In Fig 3.4, the well has 15 deviated laterals. The color legends just show different formation layers in Z direction.

Table 3.1 Base case properties

Grid Size	62×21×5
Reservoir dimensions	x×y×z (4000 ft) × (2000 ft) × (110 ft)
Porosity	30 %
Water saturation	Neglected
Permeability	
K_x	1.0 md
K_y	1.0 md
K_z	1.0 md
Formation volume factor	1.012 resbbl/stb
Viscosity	1 cp
Initial pressure	4000 psia
Bubble point pressure	100 psia

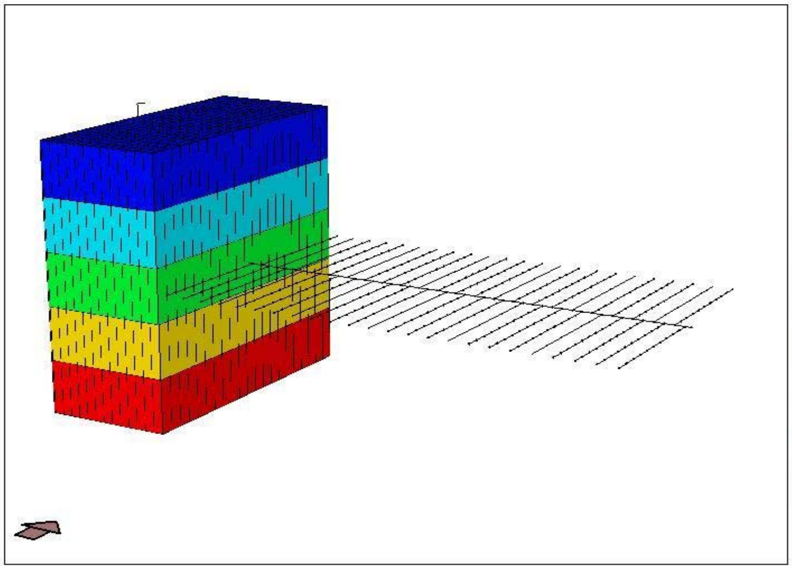


Fig 3.3 Horizontal lateral CMG model with 60 laterals

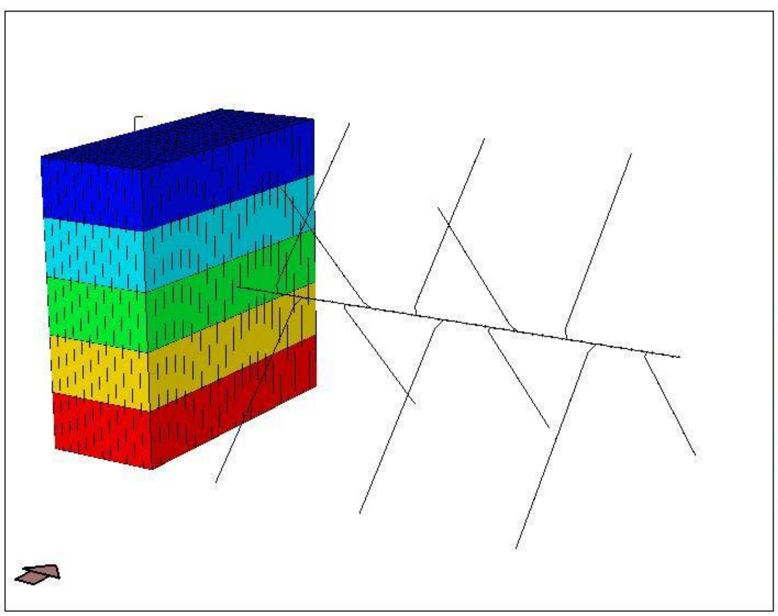


Fig 3.4 Deviated lateral CMG model with 15 laterals

3.2 Overall Productivity

The productivity index (J) is the most direct available measure of the productive capacity of a petroleum reservoir. Overall productivity index is defined as the rate that daily production of the well divided by the draw down pressure.

$$J = \frac{Q}{P_{ave} - P_{wf}} \qquad (1)$$

where Q is the volumetric production rate from the well, P_{ave} is the reservoir average pressure and P_{wf} is the flowing pressure recorded at the bottom when the flow has stabilized at the rate Q.

In order to study the performance of the multilateral well under heterogeneous reservoir conditions, in our study, we investigate the variation of the overall productivity index under the pseudo-steady-state. We use simulators to get the P_{ave} and the P_{wf} based on certain production rates. Then we calculate the overall productivity of the new well architecture in several heterogeneous reservoirs.

Under pseudo-steady-state, the boundary conditions at the top and bottom are: no flow. At the outer boundary of the reservoir in the lateral direction we assume the same condition: no flow across the boundaries. Such an idealization is often called volumetric reservoir. In addition we keep a constant (total) production rate. The stabilized pseudo-steady state is the long-time limiting behavior under such conditions, and it is characterized by a shape-preserved pressure distribution in the reservoir. Shape preserving means that all the pressure gradients are constant (with respect to time) but the pressure distribution itself is changing; in fact, it is shifted downward continuously. In such a flow regime the pressure surface shape is preserved, while the reservoir is depleted with the same (uniform) depletion rate of the pressure at every location. Such a flow regime cannot be kept forever, because the reservoir is depleted with a constant rate, and hence the wellbore pressure is also decreasing with a constant rate. Sooner or later a physical limit (or a mathematical limit of zero pressure) is reached.[14]

3.3 Numerical Methods

We take the simulation results of P_{ave} and P_{wf} directly to calculate the overall productivity index. From the CMG simulator manual, we can see the steps and equations to calculate the bottom hole pressure. The permeability influences results of pressure through the calculation of effective radius.

Effective radius r_e is defined as that radius at which the steady-state flowing pressure for the actual well is equal to the numerically calculated pressure for the well block. Clearly, the effective radius will be a function of the wellbore radius and other geometrical and porous medium parameters.

In heterogeneous reservoir, for a horizontal well parallel to the X direction:

$$r_e = 0.28 \frac{\left[\left(K_z / K_y\right)^{1/2} \Delta y^2 + \left(K_y / K_z\right)^{1/2} \Delta z^2\right]^{1/2}}{\left(K_z / K_y\right)^{1/4} + (K_y / K_z)^{1/4}} \qquad (2)$$

For a horizontal well parallel to the y direction:

$$r_e = 0.28 \frac{\left[\left(K_z / K_x\right)^{1/2} \Delta x^2 + \left(K_x / K_z\right)^{1/2} \Delta z^2\right]^{1/2}}{\left(K_z / K_x\right)^{1/4} + (K_x / K_z)^{1/4}} \qquad (3)$$

For a deviated well:

$$r_e(d) = geofac \times \sqrt{\frac{V}{\pi h(d)} \times wellfrac} \qquad (4)$$

where V is the bulk volume of the perforated grid block, and h(d) is the grid block thickness in the direction d corresponding to X, Y , Z. And geofac is the geometric factor; Wellfrac is the well fraction which is 1 for wells near block centers, 1/2 for half wells on boundaries and 1/4 for wells at block corners.

Once $r_e(d)$ has been calculated for the three directions X,Y,Z, an interpolation to the deviated wellbore direction is done as follows. Let u be a unit vector in the wellbore direction (x2-x1,y2-y1,z2-z1). Let i, j, and k be unit vectors pointing in the local X, Y, and Z directions for the block in which the layer is perforated.

$$re(u) = (re(I)\cos^2(\theta_I)\sin^2(\theta_J)\sin^2(\theta_K) + re(J)\cos^2(\theta_J)\sin^2(\theta_K)\sin^2(\theta_I) \\ + re(K)\cos^2(\theta_K)\sin^2(\theta_I)\sin^2(\theta_J))/S \qquad (5)$$

where S is the sum of the three trigonometric weighting factors.

After we use simulators to build the multilateral well models, and get the average reservoir pressure and the well bottom hole pressure from simulation results, then we can calculate the overall productivity index.

CHAPTER IV

SIMULATION IN HETEROGENEOUS RESERVOIRS

4.1 Anisotropic Reservoir Model

In some heterogeneous reservoirs, formation anisotropy shows different permeability in direction between horizontal and vertical. These anisotropic properties should be studied and simulated. To compare the influence of anisotropic property, we use the permeability factor to distinguish different anisotropic models. The permeability factor is the ratio of vertical permeability and horizontal permeability (K_v/K_h).

In order to study the performance of new multilateral wells in anisotropic reservoirs, based on basic homogeneous simulation model mentioned before, a 3-D (x-y-z) anisotropic permeability field is made by combining two kind of isotropic permeability fields with different statistics of each other. One kind of permeability is horizontal direction (x-y), and another is vertical permeability (z). For simplicity, x-y direction is considered as the main conductivity direction, and z-direction is considered as the worse conductivity direction. Then the anisotropy in the reservoir is influenced by the horizontal and vertical permeability directly.

4.1.1 Permeability Characterization

There are two main difficulties in characterizing a heterogeneous anisotropic reservoir by incorporating single well-test data. First, it is very difficult to define the radius of investigation of the anisotropic reservoir in transient single well testing. Second, the relations between well test derived permeability and grid block permeability is not defined yet on the anisotropic reservoir. [15]

Dongseong Lee[15] derived the suitable coordinate transformation method to apply the useful result achieved from the isotropic heterogeneous reservoir to the anisotropic reservoir characterization. As the first simplifying assumption, the spatial variability of reservoir properties is limited here to that of permeability. Furthermore, only lateral permeability variations are considered. The reservoir is thus modeled as two-dimensional with constant thickness. Single-phase flow is considered. Fluid properties, compressibility and porosity are uniform over the reservoir. [15]

The main steps taken in his study are as follows. The first step is to generate a base case. Anisotropic permeability variations are modeled using conditional simulation technique. The second step is a transient single well testing and its interpretation. The well testing is numerically simulated at the center of the stochastic reservoirs. The third is the derivation of a coordinate transformation through the comparison between well test permeability and individual grid block permeability. Relations of individual block permeability and well testing permeability are briefly discussed, and the coordinate transformation equations are derived for three types of anisotropic reservoirs. Then he describes the technique of simulated annealing and the procedure of heterogeneous anisotropic reservoir characterization. The characterizations are conducted for various anisotropic reservoirs. [15]

4.1.2 Model Description

Based on our homogeneous reservoir model, we just change the horizontal permeability (x-y direction) and the vertical permeability (z direction) of the reservoirs. For simplicity we let the horizontal permeability to be 1 md, and the vertical permeability to be variable from 1 md to 0.0001 md. In our anisotropic models, we simulated different kinds of well structure, and calculated the overall productivity of these models.

We use simulators to set up eight cases based on the basic reservoir model as follows:

Case 1:CMG model with 15-legs, horizontal lateral well. The construction of horizontal laterals is shown in Fig.3.3. As half of the length in Y direction of reservoir is 1000 ft, the length of the lateral from the junction on horizontal main well to the center of last simulation block is 952.38 ft.

Case 2: CMG model with 15-legs, horizontal lateral well but half penetration. Here half penetration means that the length of each lateral is half of Case 1.

Case 3: CMG model with 30-legs, horizontal lateral well. The length and direction of each lateral is the same as Case 1.

Case 4: CMG model with 30-legs, horizontal laterals but half penetration.

Case 5: CMG model with Vertical well. In this model there are four vertical wells that fully penetrate whole formation in the vertical direction.

Case 6: CMG and Eclipse model with 15-legs, deviated lateral well. The construction of laterals is shown in Fig. 3.4. Each length of the lateral is 952.38 ft, the same as Case 1. In this case we used two simulators, Eclipse and CMG. From the results, we calculate the J from Eclipse and CMG that is shown in Table 4.3.

Case 7: CMG model with 8-legs horizontal lateral well. Each length of the lateral is 952.38 ft.

Case 8: CMG model with 8-legs deviated lateral well. Each length of the lateral is 952.38 ft.

4.1.3 Simulation Results

Table 4.1 shows how the permeability factor of vertical and horizontal permeability influences the productivity index under the pseudo-steady-state. In this case, all the laterals of the well are horizontal. Table 4.2 shows the cumulative oil production and recovery factor compared between the horizontal lateral model and vertical well. As the vertical well has been perforated across the whole formation, the permeability factor did not influence the results of the productivity of that configuration. The detail of simulation results in each case has been listed in Appendix B.

Table 4.1 The overall productivity index of 15 and 30 horizontal lateral model

K_v/K_h	15-legs well J STBD/psi		30-legs well J STBD/psi	
	Case 1	Case 2	Case 3	Case 4
0.5	8.59	3.47	19.84	6.23
0.1	5.73	1.89	8.97	3.54
0.05	4.21	1.39	6.29	2.67
0.01	1.93	0.68	2.58	1.24

Table 4.2 Comparison of the 15-legs well performance to the “four vertical well” case

	Case 1				Case5			
K_v/K_h	J STBD/psi	N_p (STB)	t day	R %	J STBD/psi	N_p (STB)	t day	R %
0.5	8.59	477273	125	1.03	0.4	400,000	1000	0.86
0.1	5.73	477273	125	1.03	0.4	400,000	1000	0.86
0.05	4.21	429927	112.6	0.93	0.4	400,000	1000	0.86
0.01	1.93	305454	80	0.66	0.4	400,000	1000	0.86

We also compare the performance between the horizontal lateral model (Fig.3.3) and deviated lateral model (Fig.3.4) under a different permeability factor. In these models, the length of each lateral is the same. Table 4.3 shows how the permeability factor influences the 15-legs model with horizontal laterals and deviated laterals. Table 4.4 gives the well overall productivity of the 8-legs model.

Table 4.3 Comparison of the 15 deviated lateral model with 15 horizontal lateral model

K_v/K_h	Case 1	Case 6			
	CMG Results	Eclipse Results		CMG Results	
	J STBD/psi	J STBD/psi	J(Case6)/J(Case 1)	J STBD/psi	J(Case6)/J(Case1)
1	13.85	12.95	93.5%	13.06	94%
0.1	5.73	5.14	89.7%	5.37	93.7%
0.01	1.93	1.93	100%	2.07	107.2%
0.001	0.54	0.84	157.5%	0.81	152.6%
0.0001	0.18	*		0.31	170.1%

*at 0.0001 this model reached limitation

Table 4.4 Comparison of the 8 deviated lateral model with 8 horizontal lateral model

K_v/K_h	Case 7 J_7 STB/day/psi	Case 8 J_8 STB/day/psi	J_8/J_7
1	4.535	4.375	96.5%
0.1	2.401	2.286	95.2%
0.01	0.945	0.956	101.1%
0.001	0.311	0.441	141.8%

From the simulation results, we can draw some conclusion about that how permeability anisotropy influences the productivity of the multilateral well.

First, we investigate the results of horizontal lateral well and compare it with vertical wells. This study is based on Case 1 to Case 5.

In Table 4.1, we can see that the permeability factor is an important parameter. It greatly affects the performance of the multilateral well. When permeability ratio decreases, the overall productivity index will decrease. At a very low permeability factor of anisotropy, the multilateral well architecture is not beneficial.

From Case 1 and Case 3, they present that density of the legs affects the production. However, the optimum leg density depends on the reservoir conditions and the economic limit. The lateral penetration is another important parameter influencing the Productivity Index. When we perforated only half the length of the legs, the overall productivity index dropped. This drop is more substantial in the reservoirs with a higher permeability anisotropy factor.

In Table 4.2, compared to the vertical well configuration, the multilateral well architecture is advantageous at high permeability anisotropy factors. When the ratio of vertical to horizontal permeability is very low**,** the vertical well configuration is favorable.

Second, we investigate the different results of deviated wells compared with horizontal lateral well.

In Table 4.3, the simulation results of two models show that the productivity of horizontal lateral model is better than deviated model when the ratio of K_v vs. K_h is from 1 to 0.01. The permeability factor around 0.01 is the critical point in our model. As the ratio falls below 0.01, the deviated well is more beneficial.

Compared with 15-legs model, in Table 4.4, the 8-legs model has less productivity index. When the permeability ratio is changed from 1 to 0.01, horizontal lateral well have better performance than the deviated lateral well.

The permeability factor of anisotropy influences horizontal laterals more than the deviated well. When the ratio of K_v over K_h is changed from 1 to 0.0001, the productivity of both models decrease. But the horizontal laterals model decreases sharply than the deviated laterals model. So deviated laterals have more benefit in the anisotropic reservoir in which has a very small permeability factor.

Above all, we can see multilateral well performance will be influenced by the anisotropic property of reservoir. Permeability factor is an important parameter to describe the anisotropic reservoir.

4.2 Shale Multi-Layers Reservoir Model

In the results of anisotropic reservoir models, the reservoir heterogeneous property plays an important role in the productivity of the new multilateral well. Heterogeneities greatly affect the overall productivity index, and can reduce or completely block the flow of fluids inside a reservoir. After the permeability anisotropy of heterogeneous reservoirs has been studied, the multi-layer heterogeneity needs to be considered. In some kinds of reservoirs, there are some shale layers, which block the fluid flow by very lower permeability.

We set up a reservoir model that has two 1-feet shale layers. In this model the reservoir has constant permeability except in the 1-feet shale layers. We change the permeability of shale layers to investigate the effects on well performance. In these models, under the pseudo-steady state, the overall productivities of the horizontal lateral well and deviated lateral well are compared. These Multi-layers models will present how shale layers influence the overall productivity.

4.2.1 Permeability of Shale Layers

Permeability is one of the most important of all formation parameters that petroleum engineers use. It is used to determine whether a well should be completed, or abandoned. Extensive research on permeability has been conducted for decades on clean formations. Vertical permeability in shaly formations has long been viewed as a problem. [13]

In our early studies of reservoir models in this thesis, the reservoirs are assumed to be homogeneous or anisotropic. In these studies, the porosity-permeability transform has been used for a better description of the reservoir having some complex geological property. Clark[13] showed that if the rock grains are large and flat, uniformly arranged with the longest dimension, then the horizontal permeability (K_h) would be higher than the vertical one (K_v). Clark also showed that if the rock were composed mostly of large and uniformly rounded grain, its permeability would be considerably high and almost equal in both horizontal and vertical directions. Generally, vertical permeability is lower than horizontal permeability, especially if the sand grains are small and have irregular shape. Most petroleum reservoirs are in this category. Neasham[13] studied the effect of clay on permeability. He showed that the clay morphology of the highest air permeability is predominantly the discrete particle. Dispersed clay morphology for samples in the intermediate air permeability range is predominantly of a pore-lining variety. Hence, sands with pore-lining clays can have both significant amounts of clay and relatively good air permeability. The low permeability sandstones contain pore bridging clay types. This bridging clay morphology forms partial to complete barriers to fluid flow and can seriously impair rock permeability, even for sand of relatively high porosity and low clay content.[13]

In recent years, the technique of stochastic modeling has been widely used in reservoir characterization, providing a new method for identifying the uncertainty of reservoir characterization with different scales and data resources. In SPE paper of Lu Xiaoguang[13], a stochastic model of heterogeneous multi-layer sandstone reservoir was presented. According to the characteristics of the heterogeneous multiplayer continental sandstone reservoir in Daqing Oil Field, Sa-Pu-Gao Reservoir in Daqing Oil Field is a large shallow- water lake basin. It has the following characteristics. [13]

1. The reservoir distributes vertically with long intervals, multiple layers, and a thin single layer. The oil-bearing interval Sae-Put-Gao Reservoir in the north part of Daqing Oil Field is 300~500 m with more than 100 layers penetrated, and 120~150 m single sand layers can be further divided with a thickness of 1~3 m. The thinnest layer is only 0.2-0.4 m, and the thick distributary channel sandbody is 3~6 m. Only a few stacked channels are 10 m thick.[13]

2. The heterogeneous multi-layer continental sandbody reservoir in Daqing oil Field distributes alternatively with the various depositional facies vertically, while the facies are wide and perfectly differentiated horizontally. According to the change of framework sandbody, they can be divided into flood distributary plain facies and delta front facies. The delta front is subdivided into inner and outer front. The sandbody geometry, microfacies distribution dimension and physical properties among microfacies of various types of sandbody are greatly different. The lowest air permeability of the reservoir is 0.001 md, while the highest is more than 5 md. The areal, internal, and intra-layer heterogeneity of the reservoir is high.[13]

3. Characterized by low buried depth, the Sa-Pu-Gao reservoir has poor diagenesis. Instead, microfacies have a significant controlling effect on reservoir property.[13]

4. The oil field has a lack of outcrop data, but has rich logging data of dense wells pattern, which provides conditional data for detailed modeling.[13]

5. A large amount of development geologic study gives a deepening understanding of the sandbody types of this reservoir, and the association relation of various kinds of microfacies. The experiences of geologists and the knowledge of modern sedimentation and outcrop investigation provide depositional evidences for modeling.[13]

4.2.2 Model Description

Based on the research of the Daqing Oil Field, we build a shale layer reservoir model. This reservoir has the same drainage area of our basic homogenous reservoir model, but it has two thin layers of shaly stone. Fig. 4.2 give the 3-D view of the shale layer reservoir model.

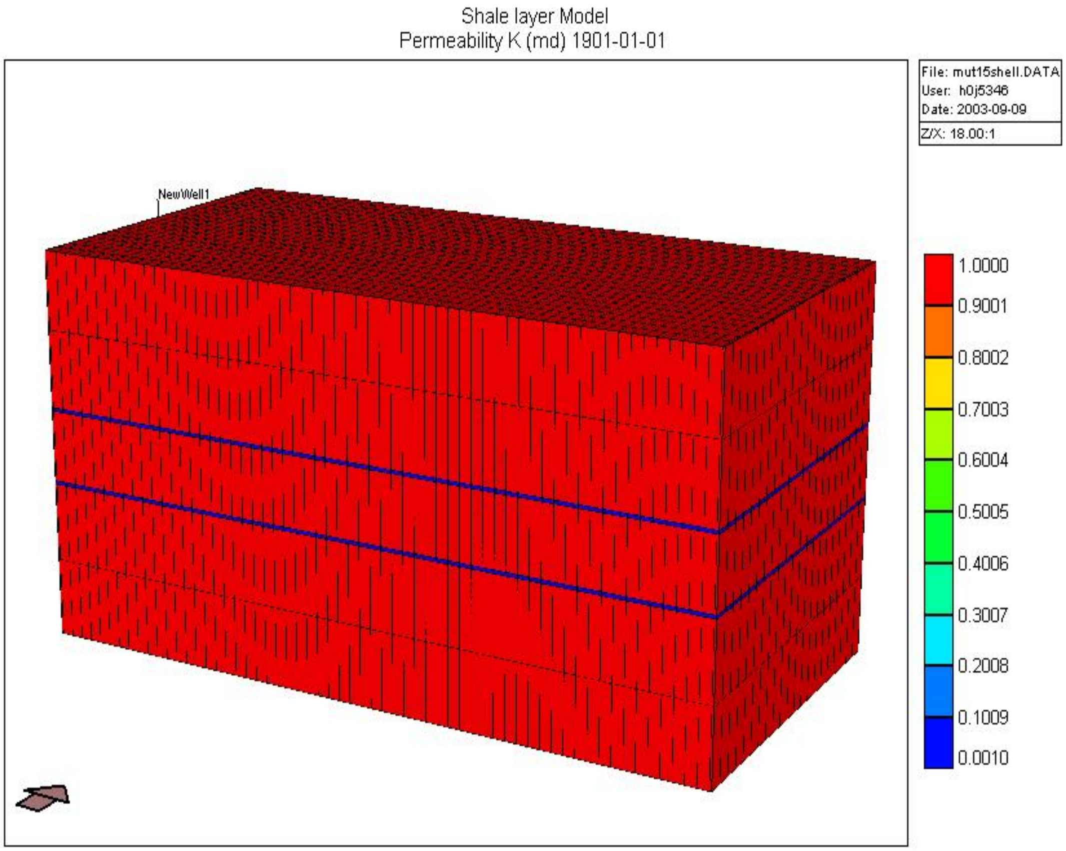


Fig. 4.2 Shale layer reservoir model

4.2.3 Simulation Results

In the multi-layer reservoir models, the overall productivities of reservoirs are simulated with series permeability of shale layers under different well structure condition. The new multilateral well has 15 legs in these models. Table 4.5 shows the results.

Table 4.5 The overall productivity index of shale model:

	Deviated lateral Well	Horizontal lateral Well
K of shale, md	J (STBD/psi)	J (STBD/psi)
0.1	12.46	10.85
0.01	10.48	8.99
0.001	7.10	5.68
0.0001	5.24	1.76

In the same reservoir condition, we build a 4-vertical-well model that fully perforated. Table 4.6 gives the results of three kinds of models. In the simulation results of vertical wells, after 175 days the bottom hole pressure declined to the limited pressure, compared with 500 days of multilateral wells.

Table 4.6 Compare multilateral well with vertical well

	Time days	Np STB	J STB/day/psi
Deviated lateral well	500	500000	7.101
Horizontal lateral well	500	500000	5.680
4 Vertical well	175	175000	0.097

These simulation results present how shale layers influence the overall productivity of our reservoir model. When the shale layer permeability changed from 0.1 to 0.0001, the productivity of the horizontal well changed from 10.86 to 1.76, and the productivity of the deviated well changed from 12.46 to 5.24. Under the same conditions, the deviated well has better productivity than the horizontal well.

Table 4.7 shows the comparisons between results of shale layer model and Case 1 of anisotropic reservoir model (Table 4.3). Both models have the same well constructor and the same initial oil in place. With horizontal lateral well, the productivities in these two models are close when the permeability factor (K_v/K_h) is 0.1 md in anisotropy reservoir and the shale layer permeability is 0.001 md in shale reservoir. With deviated lateral well, when the results are close, permeability factor (K_v/K_h) is 0.1 md and the shale permeability is 0.0001 md, in addition, when permeability factor is 0.01 and the shale permeability is 0.0001.

Table 4.7 Results of shale model and anisotropic model

	Deviated lateral Well		Horizontal lateral Well	
K of shale; K_v/K_h	J (STBD/psi)		J (STBD/psi)	
md	Case 1	Shale Model	Case 1	Shale Model
0.1	5.374	12.46	5.611	10.85
0.01	2.071	10.48	1.875	8.99
0.001	0.818	7.10	0.526	5.68
0.0001	0.313	5.24	0.184	1.76

4.3 Flow Units Model

Flow units are regions in the sedimentary sequence that control the flow of fluids within the reservoir (Hearn, 1984). Flow units are defined on the basis of not only their geologic characteristics and position in the vertical sequence but also on their petrophysical properties, especially porosity and permeability. [12] After anisotropy and shale layer were studied, the performance of new multilateral well in heterogeneous reservoir with flow units will be investigated.

4.3.1 Permeability of Flow Units

Flow unit model are built up based on the reservoir we made before. It still has the same shape of the basic model. But the property of the porosity and permeability has changed along with two different units that are randomly scattered in the reservoir.

The average porosity of the reservoir is 0.3. In the unit I, it has a high average permeability of is 1 md; on the other hand, in unit II, it has a lower average permeability of 0.001 md. In both units, the relationship of permeability and porosity is based on the rock type. Generally, permeabilities are considered as random variables with log-normal distribution that are generated by a computer program. In Fig 4.3 and Fig 4.4, the relationship of permeability and porosity is illustrated.

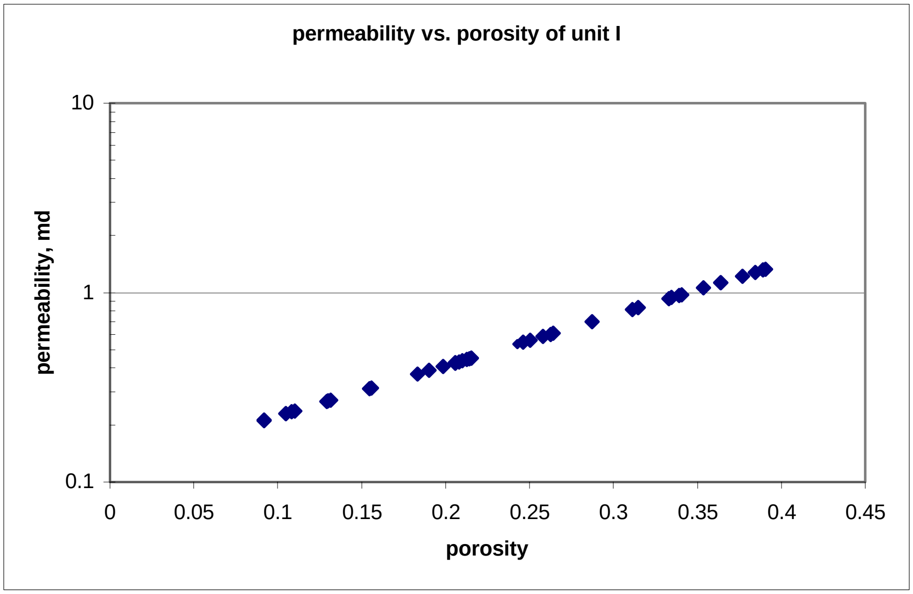


Fig. 4.3 Permeability and porosity of unit I

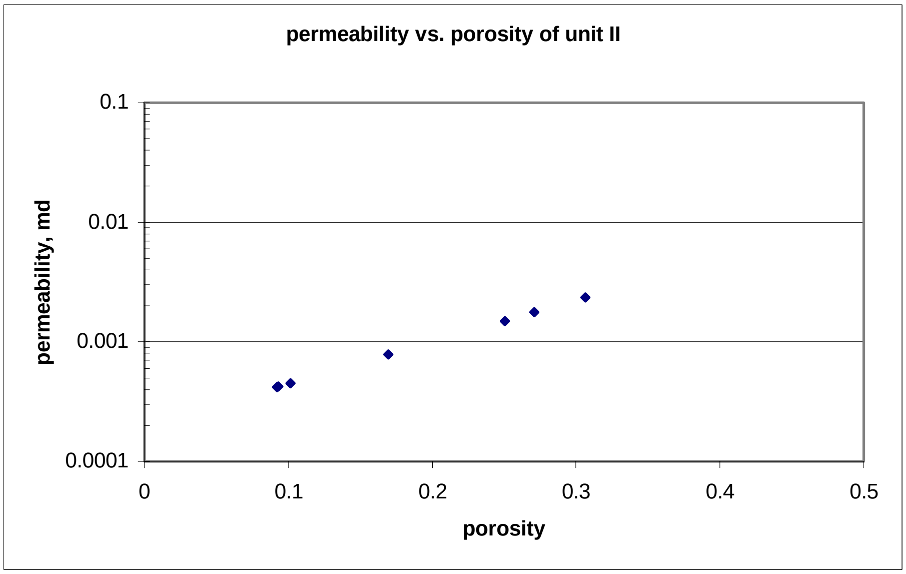


Fig. 4.4 Permeability and porosity of unit II

4.3.2 Model Description

A flow units model is built based on basic homogeneous reservoir model. This reservoir model has two flow units. These two flow units have different correlation property between porosity and permeability. The unit **I** has high average permeability, and unit **II** has lower average permeability. Then unit **I** accounts for most of the flow capacity in the reservoir. Our model will study how the distribution of the permeability of flow unit **I** and flow unit **II** affects the performance of the new multilateral well architectures.

First, in the basic reservoir model, we change the constant porosity to variable porosity for each simulation block and separate the rectangular model to two flow units. In order to compare with the basic simulation model, we fix the total pore volume of the reservoir.

Second, we use correlation between permeability and porosity to set up the distribution of permeability in the reservoir. As the two flow units have different rock types, they have a different relationship of the permeability and the porosity. At the same time, we keep the average permeability to be comparable the basic isotropic reservoir models.

Then we can change the distribution of the porosity and permeability randomly to get series reservoir models. After that, we can use simulator to study the performance of the new multilateral well architectures under these heterogeneous reservoirs.

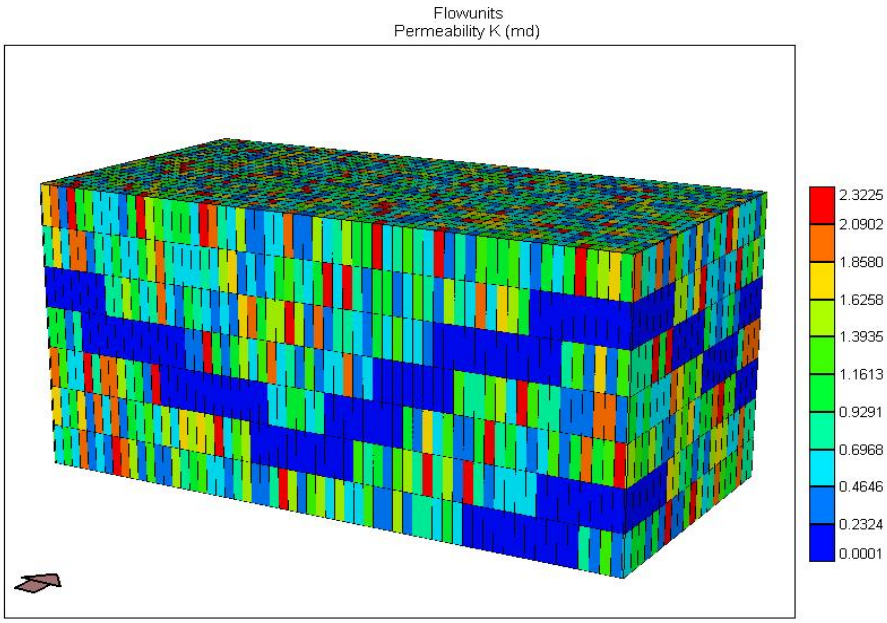


Fig. 4.5 3D view of permeability in flow units model

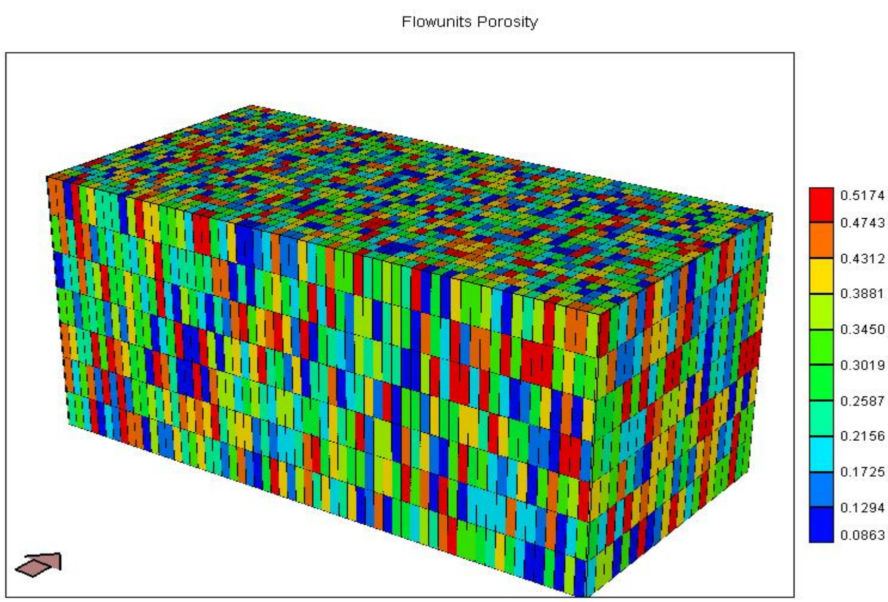


Fig. 4.6 3D view of porosity in flow units model

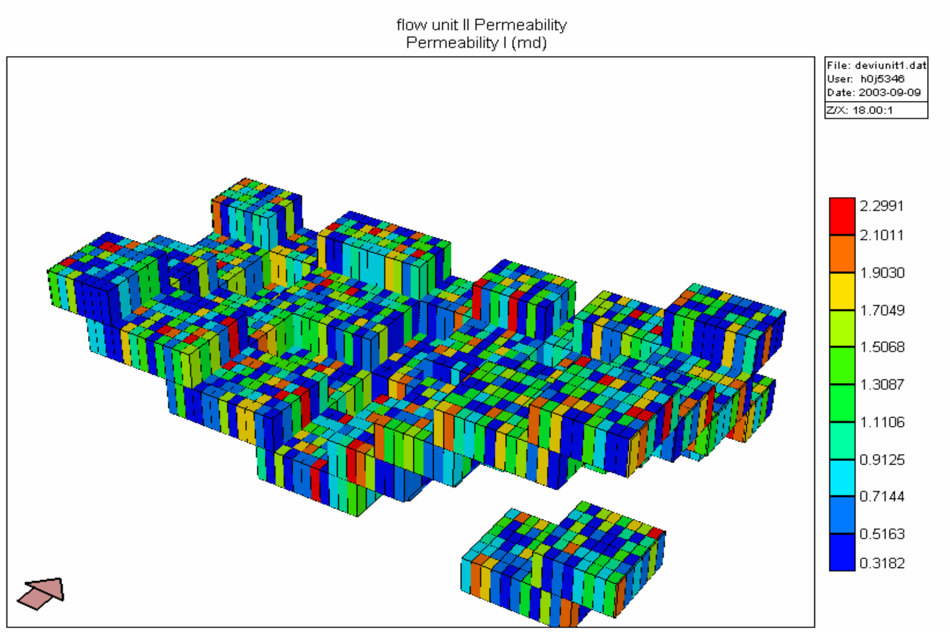


Fig. 4.7 3D view of permeability in flow unit II

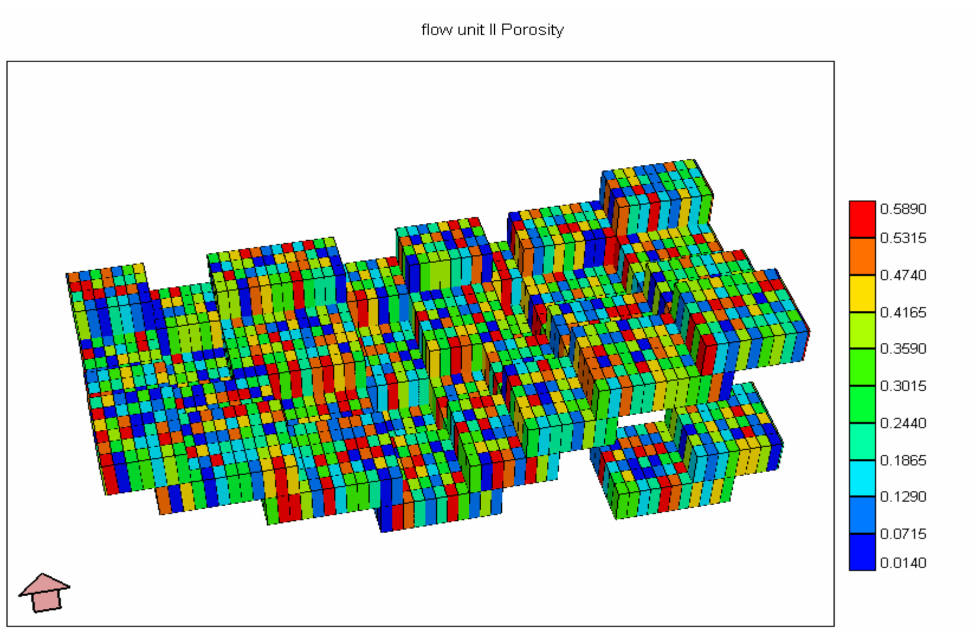


Fig. 4.8 3D view of porosity in flow units II

Fig. 4.5 shows the permeability distribution of the whole reservoir. Fig. 4.6 shows the porosity of the reservoir. Some sequences of blocks are randomly select to be flow unit II, in Fig 4.5, which has lower permeability.

Fig. 4.7 shows the permeability of flow unit II, and Fig. 4.8 shows the porosity of flow unit II. In order to show the shape of unit, the two graphs have different viewpoint.

Five cases of random permeability and porosity models are set up. The permeability distribution map of layer 4 that has a main horizontal well is given in Fig. 4.9. The areas with lower permeability (in dark color) are defined as flow unit II.

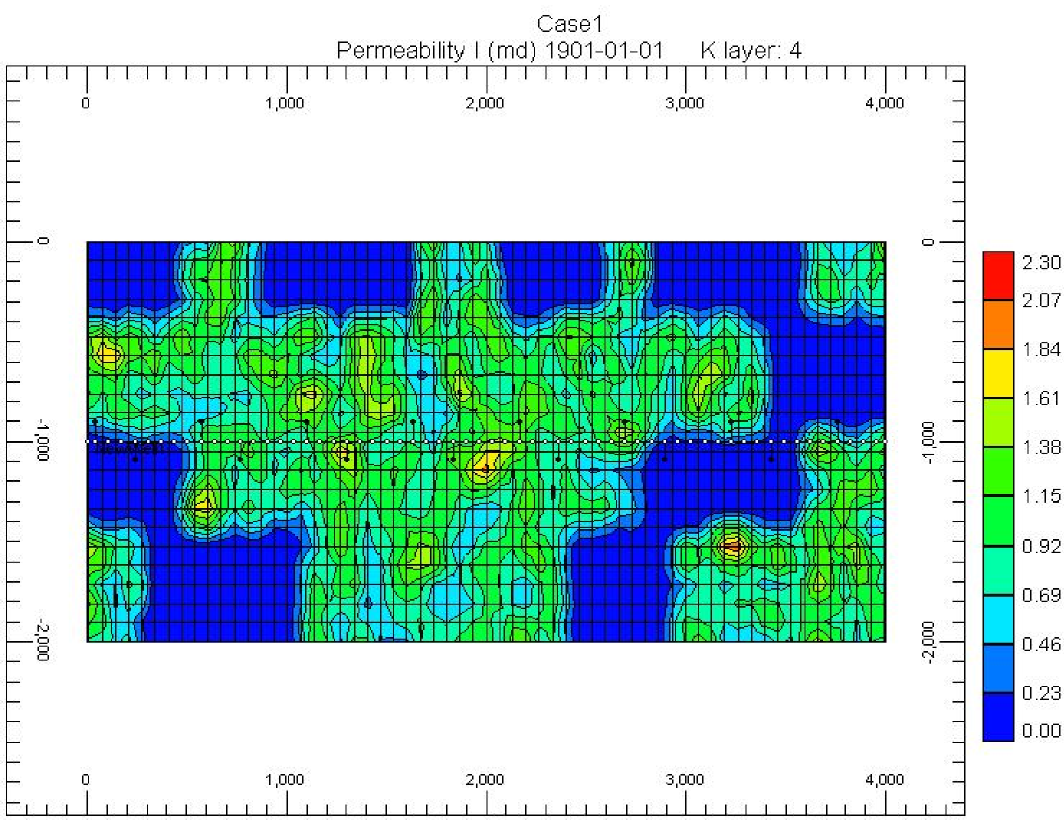
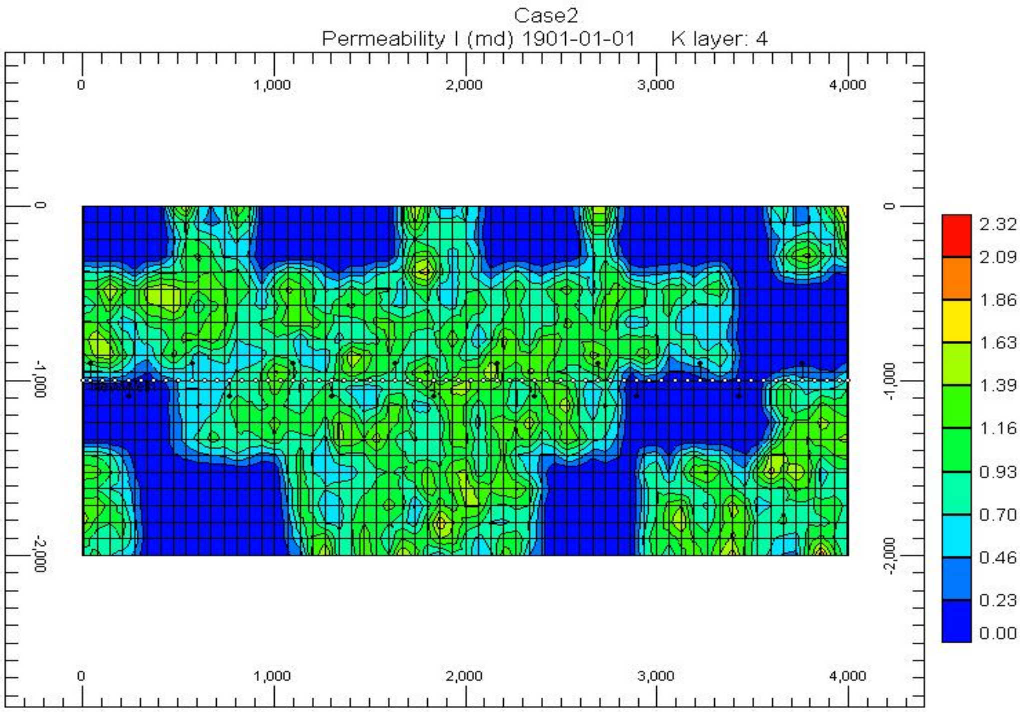


Fig. 4.9 Permeability of layer 4 in five cases



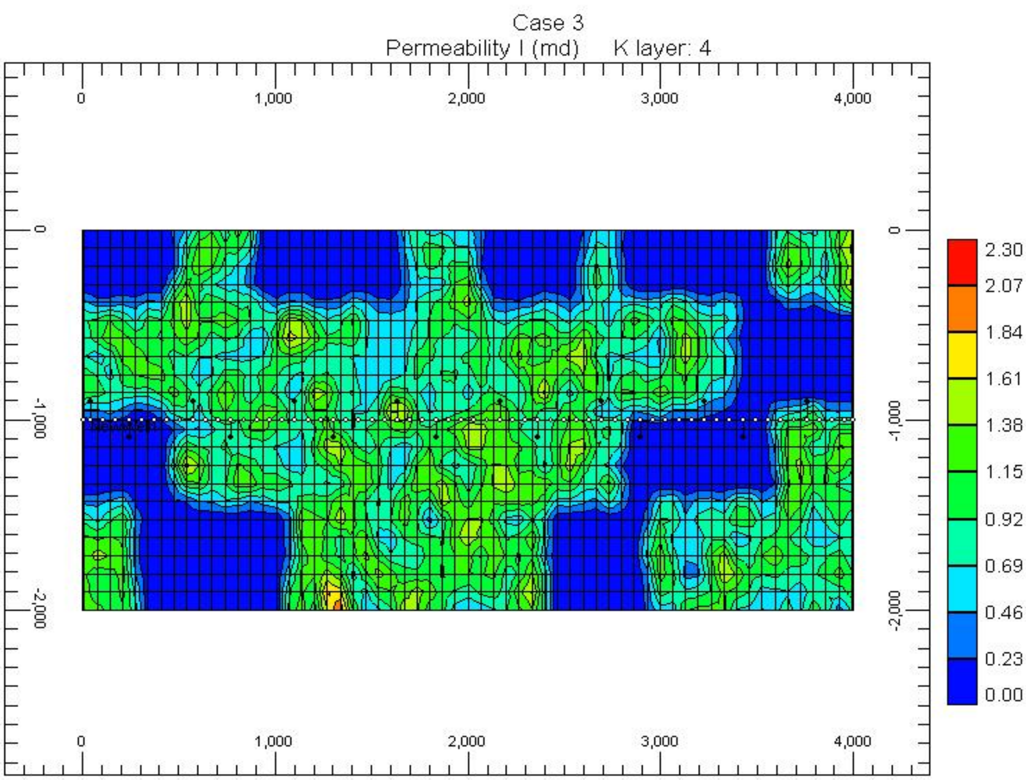
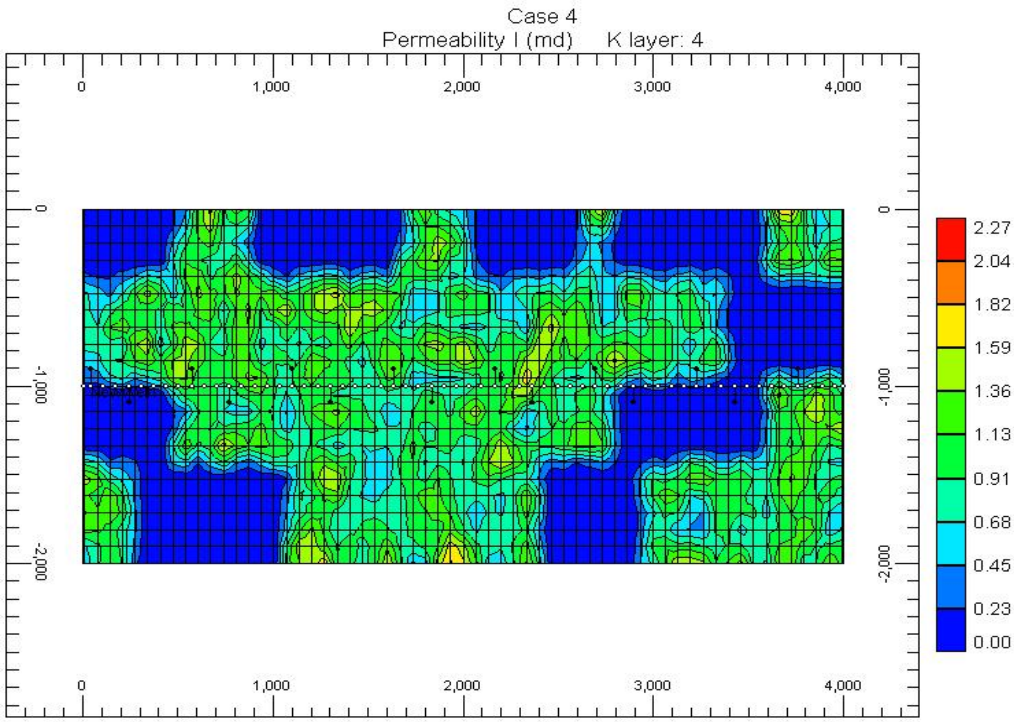


Fig. 4.9 Continued



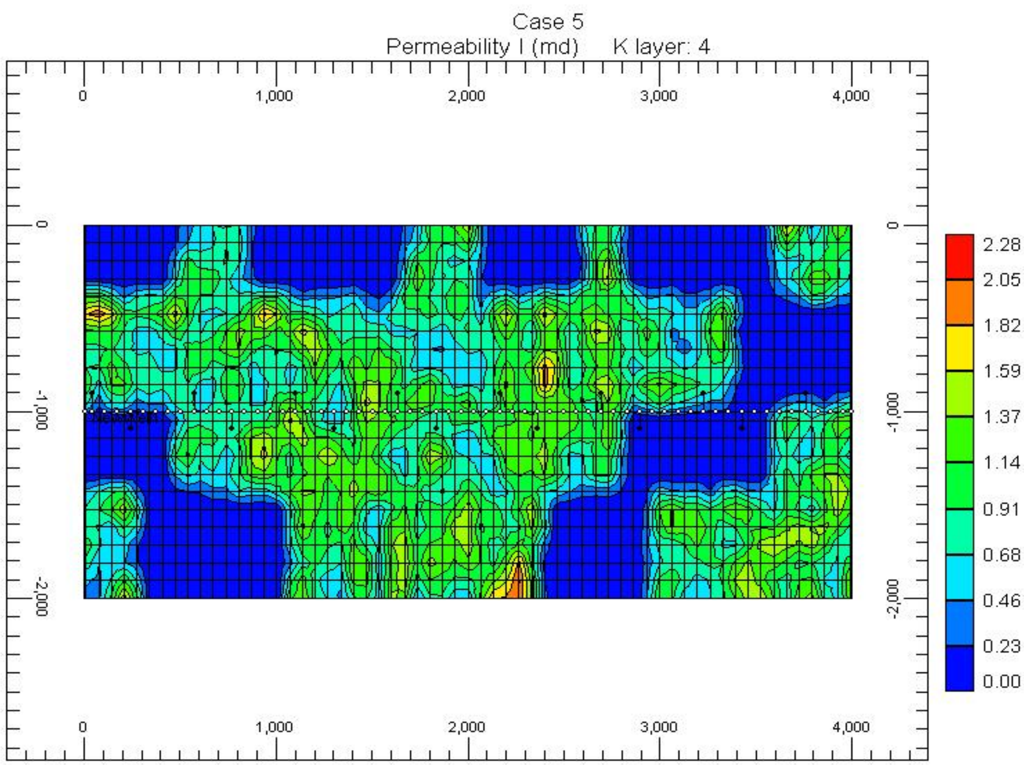


Fig. 4.9 Continued

4.3.3 Simulation Results

First, the average permeability of flow unit II is fixed at 0.001md.Then the porosity and permeability distributions are randomly changed in the reservoir. The average permeability of flow units I is fixed at1md. The reservoir average porosity is 0.3. Under five different flow unit models that have random permeability and porosity distribution, we simulated horizontal laterals and deviated laterals, and also compared the overall productivity with vertical wells. Table 4.8 gives the results.

Table 4.8 The overall productivity of five cases

	Overall Productivity J STB/day/psi		
	Horizontal Laterals	Deviated Lateral s	4 Vertical wells
Case 1	2.01	3.59	0.31
Case 2	2.02	3.90	0.31
Case 3	2.08	3.92	0.31
Case 4	1.98	3.76	0.31
Case 5	2.01	3.59	0.31

These results present that the five cases have almost the same productivity under the same well architecture. The horizontal lateral well has lower productivity compared with the deviated well. The multilateral wells have better productivity than four vertical wells.

Second, the average permeability of flow unit II is changed from 1 md to 0.00001 md. In these heterogeneous models, the horizontal lateral and deviated lateral wells are also simulated. Table 4.9 shows the results.

Table 4.9 The overall productivity under different permeability in unit II

K of unit II Md	Overall productivity J STB/day/psi		
	Horizontal Laterals	Deviated Laterals	4 Vertical wells
0.1	6.12	7.58	0.33
0.01	3.76	5.54	0.32
0.001	2.01	3.59	0.31
0.0001	0.98	1.98	0.30

These results show how the average permeability of flow unit II influences the overall productivity. When average permeability decreased, the overall productivity decreased. When permeability is under 0.01, the deviated well has better productivity.

CHAPTER V

CONCLUSION

1. New multilateral well architecture has many advantages. In our heterogeneous reservoir model, 15-laterals well has better overall productivity than four vertical wells in which have the same production constraint.

2. In anisotropic reservoirs, the difference between horizontal and vertical permeability influences the overall productivity. When the permeability factor decreased, the overall productivity also decreased. This decrease is presented in horizontal laterals more than deviated laterals.

3. In reservoirs with shale layers, the multi-layer model is useful to describe the flow block of shale layers. The average permeability of shale layer dominates the overall productivity of reservoirs.

4. Flow units in reservoir are important to overall productivity. The shape and distribution of permeability and porosity of unit should be studied in reservoir characterizations. The stochastic simulation model is useful to describe the reservoir properties.

5. Deviated lateral has better performance than horizontal lateral when the reservoir has more heterogeneity. The placement, density, and perforation length of laterals are also important for performance of new multilateral well architecture.

NOMENCLATURE

J	overall productivity index, STBD/psi.
J_7	productivity index calculated from Case 7
J_8	productivity index calculated from Case 8
Q	production, STB/day
P_{ave}	reservoir average pressure, psi
P_{wf}	well bottom hole pressure, psi
h	reservoir thickness , ft
μ	viscosity, cp
r_e	effective wellbore radius, ft.
Δx, Δy, Δz	length of well block in three dimension
$\theta(I)$, $\theta(J)$, $\theta(K)$	the angle between the wellbore direction and the X,Y,Z axes
N_p	cumulative production, STB
R	recovery factor
K_x, K_y, K_z	the permeability of X,Y,Z direction
K_v	permeability in the vertical direction, md
K_h	permeability in the horizontal direction, md

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APPENDIX A

BASIC RESERVOIR MODEL INPUT DATA FILE

This basic reservoir model is for CMG black oil simulator. The simulation model has 62 ×21× 5 grid blocks. The total length of X direction is 4000 ft, Y direction is 2000 ft, and Z direction is 110 ft. The simulation phase model is oil-water, but initial oil saturation in this reservoir is 1, and no water flood in. The permeability and porosity of this reservoir is homogeneous.

Basic simulation model input data is as follows:

```
** Simulation blocks in I,J,K direction

GRID VARI 62 21 5

KDIR DOWN

** Measurement of each block, ft

DI IVAR

10.1 60*66.33 10.1

DJ CON 95.238

DK CON 22.

**Porosity

POR CON 0.3

**Permeability In I,J,K direction, md

PERMI CON 1

PERMJ EQUALSI
```

PERMK CON 1

**Simulation phase model

MODEL *OILWATER.

In PVT data, the bubble point pressure (P_b)is 100 psi. The productivity of single phase oil well under pseudo-steady-state is studied when the bottom hole pressure is above the bubble point. When reservoir pressure is 14.7 psi, oil formation volume factor (B_o) is 1 bbl/STB. When pressure is 100 psi, B_{ob} is 1.024 bbl/STB in CMG PVT table. The B_{oi} is 1.012 bbl/STB that is the same as Eclipse simulation model. Fig. I gives the relationship of B_o and pressure.

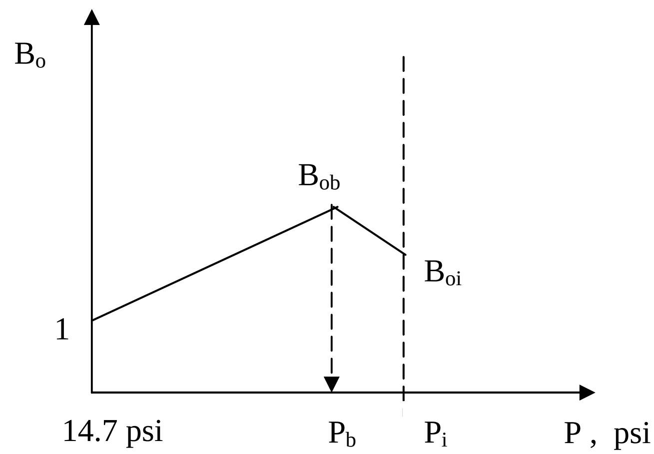

Fig. A.1 Oil formation volume factor (B_o) vs. pressure

```
** PVT table

*TRES     200.

*PVT *ZG 1

**  P       Rs          Bo      ZG      VisO    VisG

    14.7     0            1.      1.        1.      0.01

    100.     1.E-11   1.024     1.        1.      0.01

** Property of fluid

*DENSITY *OIL 50.04

*DENSITY *GAS 0.05

*DENSITY *WATER 50.04

*CO      3.E-06

*BWI     1.012

*CW      3.E-06

*REFPW    4.E+04

*VWI     1.

*CVW     0
```

The reservoir initial pressure (P_i) is 4000 psi. Fig II gives the relative permeability of oil and water. K_{row} is relative permeability of oil, and K_{rw} is the relative permability of water.

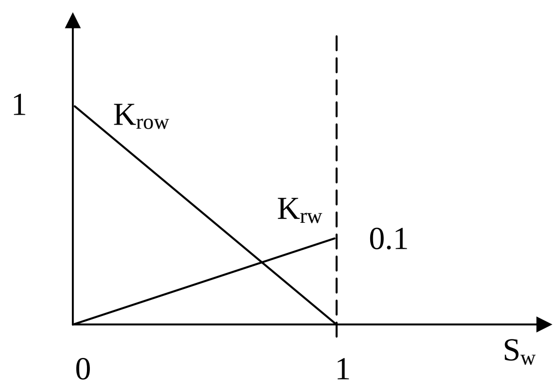

Fig. A.2 Relative permeability of oil and water

```
**Relative permeability table

*ROCKFLUID

*RPT 1

*SWT

**    SW     KRW    KROW    PCOW

0.000000  0.000000  1.000000  0.000000

1.000000  0.100000  0.000000  0.000000

*KROIL *STONE2 *SWSG
```

```
*INITIAL

*USER_INPUT

** Initial pressure , bubble point pressure, oil saturation

PRES CON 4000.

PB CON 100.

SO CON 1.

RESULTS SECTION NUMARRAYS

RESULTS SECTION GBKEYWORDS

RUN
```

In one vertical well sample model, the production constrain is that oil rate is 1000 STBD and minimum bottom hole pressure is 500 psi. Simulation time is 1000 days.

```
**Well definition

DATE 1901 01 01.

WELL  1 'NewWell1'

PRODUCER 'NewWell1'

**Well constrain of production rate and bottom hole pressure

OPERATE MAX STO  1000. CONT

OPERATE MIN BHP  500. CONT

**Well geometry data.
```

```
GEOMETRY K 0.3 0.37 1. 0.

PERF GEO   'NewWell1'

    11 11 1 1. OPEN

    11 11 2 1. OPEN

    11 11 3 1. OPEN

    11 11 4 1. OPEN

    11 11 5 1. OPEN

**Bottom hole pressure measurement point

BHPDEPTH 'NewWell1'

    5055.0

**Simulation time, day

TIME 1

TIME 10

TIME 100

TIME 200

TIME 300

TIME 400

TIME 500

TIME 1000

STOP
```

APPENDIX B

SIMULATION RESULTS OF CHAPTER IV

Table B.1 simulation results of 15 horizontal lateral model in eclipse simulator

K_v/K_h =1

T days	Q STB/day	Np STB	Pave psi	Pwf psi	J STB/day/psi
5	3818.18	19090.9	3863.0	3603.0	14.682
10	3818.18	38181.8	3726.0	3460.0	14.353
15	3818.18	57272.7	3588.9	3320.0	14.194
20	3818.18	76363.6	3451.8	3180.9	14.095
35	3818.18	133636.3	3040.0	2766.1	13.934
50	3818.18	190909	2627.7	2352.0	13.843
75	3818.18	286363.5	1939.4	1662.2	13.775
100	3818.18	381818	1249.8	971.6	13.721
150	2831.80	523408.4	224.1	14.7	13.527
200	464.64	546640.5	55.5	14.7	11.383
300	45.86	551226.8	22.2	14.7	6.102
400	4.97	551724.6	18.5	14.7	1.274
500	0.59	551784.6	18.1	14.7	0.173
900	0	551793.9	18.0	0	0
1000	0	551793.9	18.0	0	0

K_v/K_h =0.1

T days	Q STB/day	Np STB	Pave psi	Pwf psi	J STB/day/psi
3	3818.18	11454.54	3917.8	3268.4	5.872
5	3818.18	19090.9	3863.0	3203.1	5.783
10	3818.18	38181.8	3726.0	3059.2	5.728
15	3818.18	57272.7	3589.0	2918.6	5.694
20	3818.18	76363.6	3451.9	2779.0	5.675
50	3818.18	190909	2627.8	1947.4	5.613
75	3818.18	286363.5	1939.5	1255.9	5.582
100	3818.18	381818	1249.8	563.9	5.567
150	2268.69	495252.8	428.3	14.7	5.485
200	748.50	532678.3	156.8	14.7	5.263
300	151.57	547835.5	46.8	14.7	4.717
400	31.25	550960.9	24.1	14.7	3.302
500	6.55	551616.2	19.3	14.7	1.398
900	0.0101	551794.7	18.0	14.7	0.002
1000	0.0021	551794.9	18.0	14.7	0.002

Table B.1 Contibued

K_v/K_h =0.01

t days	Q STB/day	Np STB	Pave psi	Pwf psi	J STB/day/psi
1	1000	1000	3992.8	3576.6	2.402
3	1000	3000	3978.5	3500.1	2.090
5	1000	5000	3964.1	3464.3	2.001
10	1000	10000	3928.2	3411.0	1.933
15	1000	15000	3892.4	3367.1	1.903
20	1000	20000	3856.5	3327.6	1.890
35	1000	35000	3748.8	3216.8	1.879
50	1000	50000	3641.2	3107.8	1.875
75	1000	75000	3461.6	2927.2	1.871
100	1000	100000	3282.0	2746.8	1.868
150	1000	150000	2922.3	2386.1	1.864
200	1000	200000	2562.3	2025.3	1.862
300	1000	300000	1841.1	1302.8	1.857
400	1000	400000	1118.3	578.8	1.853
500	871.7	487177.1	487.0	14.7	1.845
900	29.28	549598.9	34.1	14.7	1.503
1000	12.50	550849.2	25.1	14.7	1.203

K_v/K_h =0.001

t days	Q STB/day	Np STB	Pave psi	Pwf psi	J STB/day/psi
1	1000	1000	3992.9	2965.2	0.973
3	1000	3000	3978.6	2773.2	0.829
5	1000	5000	3964.2	2658.7	0.765
10	1000	10000	3928.4	2476.1	0.688
15	1000	15000	3892.5	2338.2	0.643
20	1000	20000	3856.6	2224.9	0.612
35	1000	35000	3749.0	1976.3	0.564
50	1000	50000	3641.3	1774.5	0.535
75	1000	75000	3461.7	1501.3	0.510
100	1000	100000	3282.0	1263.4	0.495
150	1000	150000	2922.3	848.5	0.482
200	1000	200000	2562.3	461.3	0.475
300	887.47	288747.9	1922.3	14.7	0.465
400	646.87	353434.9	1455.1	14.7	0.449
500	484.57	401892	1104.6	14.7	0.444
900	157.97	502736.3	374.1	14.7	0.439
1000	119.49	514686.1	287.5	14.7	0.438

Table B.2 simulation results of 15 deviated lateral model in eclipse simulator

K_v/K_h =1

t days	Q STB/day	Np STB	Pave psi	Pwf psi	J STB/day/psi
1	3818.18	3818.18	3972.6	3732.2	15.885
3	3818.18	11454.54	3917.8	3649.2	14.216
5	3818.18	19090.9	3863.0	3585.3	13.751
10	3818.18	38181.8	3726.0	3441.7	13.430
15	3818.18	57272.7	3588.9	3301.3	13.277
20	3818.18	76363.6	3451.8	3162.1	13.179
35	3818.18	133636.3	3040.0	2747.0	13.033
50	3818.18	190909	2627.7	2332.8	12.950
75	3818.18	286363.5	1939.4	1642.9	12.879
100	3818.18	381818	1249.6	952.1	12.833
150	2798.41	521738.6	236.0	14.7	12.642
200	485.94	546035.8	59.70	14.7	10.798
300	50.71	551107.4	22.87	14.7	6.201
400	5.76	551683.6	18.69	14.7	1.442
500	0.71	551755.3	18.17	14.7	0.206
900	0	551766.8	18.09	14.7	0

K_v/K_h =0.1

T days	Q STB/day	Np STB	Pave psi	Pwf psi	J STB/day/psi
1	3818.18	3818.18	3972.6	3345.6	6.086
3	3818.18	11454.54	3917.8	3223.2	5.496
5	3818.18	19090.9	3863.1	3149.6	5.351
10	3818.18	38181.8	3726.1	3000.9	5.265
15	3818.18	57272.7	3589.1	2858.6	5.227
20	3818.18	76363.6	3451.8	2718.2	5.204
35	3818.18	133636.3	3040.1	2301.2	5.167
50	3818.18	190909	2627.7	1885.4	5.143
75	3818.18	286363.5	1939.4	1193.6	5.119
100	3818.18	381818	1249.7	501.4	5.102
150	2199.80	491808.4	453.2	14.7	5.016
200	769.51	530284.4	174.1	14.7	4.827
300	167.26	547010.9	52.6	14.7	4.404
400	36.93	550704	25.8	14.7	3.309
500	8.266	551530.6	19.8	14.7	1.602
900	0.023	551773.3	18.09	14.7	0.006
1000	0.005	551773.9	18.09	14.7	0.001

Table B.2 Continued

K_v/K_h =0.01

t days	Q STB/day	Np STB	Pave psi	Pwf psi	J STB/day/psi
1	1000	1000	3992.8	3584.0	2.446
3	1000	3000	3978.5	3511.9	2.143
5	1000	5000	3964.1	3476.6	2.051
10	1000	10000	3928.2	3424.5	1.984
15	1000	15000	3892.4	3381.7	1.958
20	1000	20000	3856.5	3342.8	1.946
35	1000	35000	3748.8	3232.3	1.936
50	1000	50000	3641.1	3123.2	1.930
75	1000	75000	3461.6	2942.4	1.925
100	1000	100000	3282.0	2761.9	1.922
150	1000	150000	2922.3	2401.1	1.918
200	1000	200000	2562.3	2040.2	1.915
300	1000	300000	1841.0	1317.7	1.910
400	1000	400000	1118.2	593.6	1.906
500	882.2	488223.1	479.3	14.7	1.898
900	27.7	549741.9	32.9	14.7	1.517

K_v/K_h =0.001

t days	Q STB/day	Np STB	Pave psi	Pwf psi	J STB/day/psi
1	1000	1000	3992.9	3081.0	1.096
3	1000	3000	3978.5	2944.8	0.967
5	1000	5000	3964.2	2883.7	0.925
10	1000	10000	3928.3	2803.4	0.888
15	1000	15000	3892.5	2744.8	0.871
20	1000	20000	3856.6	2695.6	0.861
35	1000	35000	3748.9	2571.9	0.849
50	1000	50000	3641.2	2456.5	0.844
75	1000	75000	3461.7	2271.5	0.840
100	1000	100000	3282.1	2088.7	0.837
150	1000	150000	2922.4	1725.5	0.835
200	1000	200000	2562.4	1362.8	0.833
300	1000	300000	1841.1	637.8	0.831
400	946.1	394612.1	1157.3	14.7	0.828
500	586.4	453258.5	732.7	14.7	0.816
900	90.6	536419.7	129.6	14.7	0.788
1000	56.9	542117	88.2	14.7	0.774

Table B.3 Simulation results of 15 deviated lateral model in CMG simulator

K_v/K_h =1

t days	Pave psi	Pwf psi	Q STB/day	J STB/day/psi
10	3729.1	3448.37	3818.18	13.597
20	3457.9	3171.67	3818.18	13.335
30	3186.3	2897.19	3818.18	13.203
40	2914.3	2623.28	3818.18	13.119
50	2641.7	2349.49	3818.18	13.062
60	2368.8	2075.61	3818.18	13.021
70	2095.4	1801.52	3818.18	12.991
80	1821.5	1527.12	3818.18	12.968
90	1547.2	1252.37	3818.18	12.949
100	1272.4	977.236	3818.18	12.933
150	536.1	500	387.5	10.730
200	505.1	500	44.9	8.847
300	500.7	500	5.9	8.081
400	500.1	500	0.8	7.584
500	500.0	500	0.1	7.343
750	500.001	500	0.0095	9.5
1000	500	500	0	0

K_v/K_h =0.1

t days	Pave psi	Pwf psi	Q STB/day	J STB/day/psi
5.030234	3863.7	3180.6	3818.18	5.585
10	3729.1	3033.8	3818.18	5.490
20	3457.9	2755.9	3818.18	5.439
40	2914.2	2205.7	3818.18	5.389
50	2641.7	1931.1	3818.18	5.373
60	2368.7	1656.5	3818.18	5.361
70	2095.3	1381.7	3818.18	5.350
80	1821.4	1106.7	3818.18	5.342
90	1547.1	831.4	3818.18	5.334
100	1272.4	555.7	3818.18	5.327
150	638.4	500	695.5	5.023
200	538.6	500	189.6	4.906
250	514.0	500	67.9	4.834
300	505.1	500	24.5	4.768
400	501.1	500	5.5	4.697
500	500.2	500	1.2	4.632
750	500.029	500	0.13	4.568
1000	500.003	500	0.014	4.708

Table B.3 Continued

K_v/K_h =0.01

t days	Pave psi	Pwf psi	Q STBD	J STBD/psi
10	3929.0	3463.1	1000	2.146
20	3858.1	3381.2	1000	2.096
30	3787.1	3306.7	1000	2.081
40	3716.1	3234.1	1000	2.074
50	3645.1	3162.2	1000	2.070
60	3574.1	3090.5	1000	2.067
70	3503.0	3018.9	1000	2.065
80	3431.8	2947.4	1000	2.064
90	3360.5	2875.9	1000	2.062
100	3289.7	2804.4	1000	2.061
150	2933.5	2447.5	1000	2.057
200	2576.6	2089.2	1000	2.054
300	1860.7	1372.3	1000	2.049
400	1141.6	652.5	1000	2.044
500	668.4	500	330.4	1.961
745	523.3	500	46.1	1.978
1000	505.0	500	9.9	1.971

K_v/K_h =0.001

t days	Pave psi	Pwf psi	Q STBD	J STBD/psi
10	3929.0	2759.9	1000	0.855
20	3858.1	2661.8	1000	0.835
30	3787.7	2577.0	1000	0.826
40	3716.1	2498.9	1000	0.821
50	3645.1	2423.6	1000	0.818
60	3574.8	2349.7	1000	0.816
70	3502.9	2276.6	1000	0.815
80	3431.8	2203.9	1000	0.814
90	3360.7	2131.6	1000	0.813
100	3289.5	2059.3	1000	0.812
150	2933.4	1700.1	1000	0.810
200	2576.6	1340.1	1000	0.809
300	1860.7	620.7	1000	0.806
400	1283.1	500	620.4	0.792
500	973.6	500	375.3	0.792
859	599.98	500	78.8	0.788
1000	555.57	500	43.7	0.787

Table B.4 The average overall productivity index at pseudo-steady-state

	J STBD /psi		
	Table 5	Table6	Table7
K_v/K_h =1	13.780	12.887	12.950
K_v/K_h =0.1	5.587	5.121	5.334
K_v/K_h =0.01	1.857	1.910	2.044
K_v/K_h =0.001	0.484	0.833	0.808

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